

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)**ScienceDirect**

Procedia Engineering 133 (2015) 320 – 347

**Procedia  
Engineering**[www.elsevier.com/locate/procedia](http://www.elsevier.com/locate/procedia)

6th Fatigue Design conference, Fatigue Design 2015

## Fatigue Assessment for In-Service Components – A New Part for API 579-1/ASME FFS-1 Fitness-For-Service

David A. Osage\*

*E<sup>2</sup>G | The Equity Engineering Group, Inc., 20600 Chagrin Blvd., Suite 1200, Shaker Heights, 44122, USA*

---

### Abstract

The third edition of API 579-1/ASME FFS-1 Fitness-For-Service will include a new Part covering fatigue assessment procedures for in-service components. Fitness-For-Service (FFS) assessments are quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage, or that may be operating under a specific condition that might cause a failure. The API 579-1/ASME FFS-1 Standard was specifically written to cover in-service pressurized equipment typically found in the refining and petrochemical industries as well as the fossil utility industry. The new Part will cover methods used to estimate the time to crack initiation using a strain-life approach and will be written as a multi-tiered approach covering screening, current design code methods, and advanced methods that take into account the latest in technology. The screening and design code assessment methods in the new Part will be based on an updated version of the procedures in the ASME B&PV Code, Section VIII, Division 2. The advanced methods will include next generation versions for the fatigue assessment of welded joints, the Master S-N Curve Method as described in WRC 523, and the Verity Fatigue Assessment Method developed by Battelle. The advanced methods will also include a new smooth-bar fatigue assessment method that incorporates a multi-axial fatigue criterion with a critical plane approach. Cycle counting methods for both welded joint and smooth-bar fatigue methods will be provided. Methods to evaluate fatigue in the subcritical crack-growth regime in API 579-1/ASME FFS-1 using a fracture mechanics approach are also covered.

© 2015 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of CETIM

**Keywords:** Fatigue; Crack Growth; Crack Initiation; Cycles to Failure; Time to Failure; API 579-1/ASME FFS-1.

---

---

\* Corresponding author. Tel.: +1-216-658-4789

E-mail address: [daosage@equityeng.com](mailto:daosage@equityeng.com)

## 1. Introduction

The ASME and API design codes and standards for pressurized equipment provide rules for the design, fabrication, inspection, and testing of new pressure vessels, piping systems, and storage tanks. These codes typically do not provide assessment procedures to evaluate degradation due to in-service, environmentally-induced damage, or flaws from original fabrication that may be found during subsequent inspections. Fitness-For-Service (FFS) assessments are quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component containing a flaw or damage. The API 579-1/ASME FFS-1 Standard was developed to provide guidance for conducting FFS assessments of flaws commonly encountered in the refining and petrochemical industry that occur in pressure vessels, piping, and tankage. However, the assessment procedures in API 579-1/ASME FFS-1 have been used to evaluate flaws encountered in other industries such as the pulp and paper industry, fossil electric power industry, and nuclear industry. The results from a FFS assessment may be used to make, run, rerate, repair, or replace decisions to ensure that pressurized equipment containing flaws that have been identified during an inspection can continue to operate safely.

In the second edition of API 579-1/ASME FFS-1, two forms of fatigue are addressed, crack initiation using a strain-life equation and subcritical crack-growth based on fracture mechanics. The strain-life approach to fatigue was addressed in an annex to support the assessment of other damage mechanics, while subcritical crack-growth was addressed in Part 9 covering crack-like flaws. The third edition of API 579-1/ASME FFS-1 includes a major reorganization whereby annexes were re-deployed to the Parts with a similar topic. During the reorganization it was decided that fatigue using a strain-life approach should be removed from an annex and included in a new Part. This was a significant decision as each Part in API 579-1/ASME FFS-1 not only includes assessment techniques but also provides recommendations for in-service monitoring and remediation methods.

In this paper a review of fatigue assessment methods based on subcritical crack-growth is provided first. The fracture mechanics methods used for subcritical crack-growth that are described are based on the well-known Failure Assessment Diagram (FAD) described in reference [1]. The FAD utilizes an engineering approach that extends elastic fracture mechanics concepts to cover elastic-plastic fracture mechanics and plastic collapse. The second part of the paper is devoted to the new Part 14 covering strain-life approaches for fatigue. Four methods are described that utilize strain-like concepts based on smooth bar and welded joint fatigue curves. These methods include legacy ASME techniques that have been updated to include more modern cycle counting techniques, and a new critical plane approach based on the Brown-Miller strain-life equation, a rainflow cycle counting method with multiple channels, and an incremental multiaxial Neuber plasticity correction using the nonlinear kinematic-hardening model of Chaboche.

### Nomenclature

|                           |  |
|---------------------------|--|
| $b_k$                     | exponent in Brown-Miller strain-life equation.   |
| $c_k$                     | exponent in Brown-Miller strain-life equation.   |
| $C$                       | fatigue crack-growth coefficient.  |
| $D$                       | time-dependent crack-growth coefficient.   |
| $da/dN$                   | crack-growth as a function of cycles.  |
| $da/dt$                   | crack-growth as a function of time.  |
| $\Delta e_{ij,k}$         | change in elastic strain range at the point under evaluation for the $k^{th}$ cycle.                 |
| $\Delta \epsilon_k$       | local nonlinear structural strain range at the point under evaluation for the $k^{th}$ cycle.        |
| $\Delta \epsilon_{peq,k}$ | equivalent plastic strain range for the $k^{th}$ loading condition or cycle.                         |
| $\Delta \epsilon_k^e$     | elastically calculated structural strain range at the point under evaluation for the $k^{th}$ cycle. |

|                          |   |
|--------------------------|---|
| $\Delta\epsilon_{eff,k}$ | effective strain range for the $k^{th}$ cycle.  |
| $\Delta\epsilon_{e,k}$   | equivalent elastic strain range for the $k^{th}$ loading condition or cycle.                                  |
| $\Delta\epsilon_{peq,k}$ | equivalent plastic strain range for the $k^{th}$ loading condition or cycle.                                  |
| $\Delta\epsilon_{N,k}$   | normal strain range on the critical plane for the $k^{th}$ cycle.   |
| $\Delta\gamma_k$         | shear strain range on the critical plane for the $k^{th}$ cycle.  |
| $\Delta K$               | applied stress intensity factor range.  |
| $\Delta p_{ij,k}$        | change in plastic strain range at the point under evaluation for the $k^{th}$ cycle.                          |
| $\Delta S_{P,k}$         | range of primary plus secondary plus peak equivalent stress for the $k^{th}$ cycle.                           |
| $\Delta S_{ess,k}$       | range of equivalent structural stress for the $k^{th}$ cycle.   |
| $\Delta\sigma_k$         | structural stress range at the point under evaluation for the $k^{th}$ cycle.                                 |
| $\Delta\sigma_{ij,k}$    | stress tensor range at the point under evaluation for the $k^{th}$ cycle.                                     |
| $\Delta\sigma_k^e$       | elastically calculated structural stress range at the point under evaluation for the $k^{th}$ cycle.          |
| $\Delta\sigma_{b,k}^e$   | elastically calculated structural bending stress range at the point under evaluation for the $k^{th}$ cycle.  |
| $\Delta\sigma_{m,k}^e$   | elastically calculated structural membrane stress range at the point under evaluation for the $k^{th}$ cycle. |
| $E_{yf}$                 | value of modulus of elasticity on the fatigue curve being utilized.   |
| $E_{ya,k}$               | value of modulus of elasticity evaluated at the mean temperature of the $k^{th}$ cycle.                       |
| $\mathcal{E}_{f,k}$      | strain-life equation parameter for the $k^{th}$ cycle.  |
| $F$                      | peak equivalent stress.   |
| $f_{M,k}$                | mean stress correction factor for the $k^{th}$ cycle.   |
| $I$                      | correction factor used in the structural stress evaluation.   |
| $K$                      | applied stress intensity factor.  |
| $K_{css}$                | parameter for the cyclic stress-strain curve.   |
| $K_{e,k}$                | fatigue penalty factor for the $k^{th}$ cycle   |
| $K_I^P$                  | stress intensity factor based on primary stresses.  |
| $K_I^{SR}$               | stress intensity factor based on secondary and residual stresses.   |
| $K_{mat}$                | value of the material fracture toughness used in the assessment.  |
| $K_r$                    | toughness ratio.  |
| $L_r$                    | load ratio based on primary stress.   |
| $m$                      | time-dependent crack-growth coefficient.  |
| $m_{ss}$                 | exponent used in a fatigue analysis based on the structural stress.   |
| $N_{f,k}$                | number of cycles to failure for the $k^{th}$ cycle.   |
| $n$                      | fatigue crack-growth exponent for fatigue.  |
| $n_{css}$                | material parameter for the cyclic stress-strain curve model.  |
| $P_b$                    | primary bending equivalent stress.  |

|                     |   |
|---------------------|---|
| $P_L$               | local primary membrane equivalent stress.   |
| $P_m$               | general primary membrane equivalent stress.   |
| $Q$                 | secondary equivalent stress.  |
| $R_k$               | stress ratio for the $k^{th}$ cycle.  |
| $R_{b,k}$           | ratio of the bending stress to the membrane plus bending stress for the $k^{th}$ cycle. |
| $S$                 | allowable primary stress.   |
| $S_a$               | allowable cyclic stress established from a fatigue curve.                               |
| $S_{alt,k}$         | alternating equivalent stress for the $k^{th}$ cycle.                                   |
| $S_{ps}$            | allowable primary plus secondary stress.  |
| $S_{y,k}$           | yield strength of the material evaluated at the mean temperature of the $k^{th}$ cycle. |
| $\sigma'_{f,k}$     | strain-life equation parameter for the $k^{th}$ cycle.                                  |
| $\sigma_{max,k}$    | maximum stress for the $k^{th}$ cycle.  |
| $\sigma_{min,k}$    | minimum stress for the $k^{th}$ cycle.  |
| $\sigma_{N-mean,k}$ | normal mean stress on the critical plane in the $k^{th}$ cycle.                         |
| $\sigma_{ys}$       | yield strength at the assessment temperature.   |
| $\sigma_{ref}^P$    | reference stress based on the primary stress.   |
| $\sigma_{ref}^{SR}$ | reference stress based on the secondary and residual stress.                            |
| $t_{ess}$           | equivalent structural stress effective thickness.                                       |
| $\Phi$              | plasticity corrector factor.  |

## 2. Overview of the API 579-1/ASME FFS-1 Standard

The first edition of API 579 Recommended Practice for Fitness-For-Service [2] published in 2000 (API 579 2000) was developed to provide guidance for conducting FFS assessments of flaws commonly encountered in the refining and petrochemical industry that occur in pressure vessels, piping, and tankage. This recommended practice quickly became the de facto international FFS Standard for pressure containing equipment in the refining and petrochemical industries. The assessment procedures in API 579 2000 were used to evaluate flaws encountered in other industries such as the pulp and paper industry, fossil electric power industry, and the non-commercial nuclear industry. Because of the general interest and applicability of FFS technology to multiple industries, API and ASME combined resources and created the API/ASME Joint committee on Fitness-For-Service (FFSJC) in 2002. In 2007, the FFSJC produced a new FFS standard entitled API 579-1/ASME FFS-1 2007 Fitness-For-Service [3]. The API 579-1/ASME FFS-1 2007 standard included all topics contained in API 579 2000 and also included new parts covering FFS assessment procedures that address unique damage mechanisms experienced by other industries. API 579-1/ASME FFS-1 2007 superseded the API 579-2000 that was subsequently withdrawn.

The FFSJC is currently working on the next release of API 579-1/ASME FFS-1 that will be issued at the end of 2015. The new release will include many planned technical improvements to further address industry needs. These improvements include the addition of a new part on fatigue evaluation, updates to the assessment procedures for crack-like flaws, remaining life assessments for components operating at elevated temperatures, and a rewrite of residual stress solutions for use in the evaluation of crack-like flaws based on the latest state-of-the-art approaches.

## 2.1. Organization

API 579-1/ASME FFS-1 is a highly structured document designed to facilitate use by practitioners and to facilitate future enhancements and modifications by the FFSJC. Part 1 of the document covers: introduction and scope; responsibilities of the Owner-User, Inspector, and Engineer; qualification requirements for the Inspector and Engineer; and references to other codes and standards. An outline of the overall FFS assessment methodology that is common to all assessment procedures included in API 579-1/ASME FFS-1 is provided in Part 2 of the document. The organization of Part 2 and all subsequent parts that contain FFS assessment procedures is shown in Table 1.

Table 1 – Organization of Each Part in API 579-1/ASME FFS-1

| Section  | Description   |
|--|---|
| General  | The scope and overall requirements for an FFS assessment are provided.  |
| Applicability and Limitations of the FFS Assessment Procedures | The applicability and limitations for each FFS assessment procedure are indicated; these limitations are stated in the front of each part for quick reference.  |
| Data Requirements  | The data requirements for the FFS assessment are outlined; these data requirements include; Original equipment design data, Maintenance and operational history, Data/measurements for a FFS assessment, Recommendations for inspection technique and sizing requirements.  |
| Assessment Techniques and Acceptance Criteria                  | Detailed assessment rules are provided for three levels of assessment: Level 1, Level 2, and Level 3. A discussion of these assessment levels is covered in the body of this paper.   |
| Remaining Life Evaluation                                      | Guidelines for performing a remaining life estimate are provided for the purpose of establishing an inspection interval in conjunction with the equipment's governing inspection code.  |
| Remediation  | Guidelines are presented on methods to mitigate and/or control future damage. In many cases, changes can be made to the component or to the operating conditions to mitigate damage progression.  |
| In-Service Monitoring  | Guidelines for monitoring damage while the component is in-service are provided. These guidelines are useful if a future damage rate cannot be estimated easily or the estimated remaining life is short. In-service monitoring is one method whereby future damage or conditions leading to future damage can be assessed or confidence in the remaining life estimate can be increased. |
| Documentation  | Guidelines for documentation for an assessment are provided. The general rule is that a practitioner should be able to repeat the analysis from the documentation without consulting an individual originally involved in the FFS assessment.   |
| References   | A comprehensive list of technical references used in the development of the FFS assessment procedures is provided. References to codes and standards are also provided.   |
| Tables and Figures   | Tables and figures including logic diagrams are used extensively in each part to clarify assessment rules and procedures.   |

Note, that in the organization shown in Table 2, sections covering remaining life evaluation, remediation, and in-service monitoring are key aspects to a FFS standard because it is recognized that not all forms of damage can be modeled, and a combination of approaches is typically required to assure continued safe operation of pressurized equipment with known flaws or damage. The remaining life evaluation is used to establish a safe operating period and also an inspection interval. This represents the union between a FFS standard and in-service inspection standards mandated many jurisdictions.

Starting with Part 3, a catalogue of FFS assessment procedures organized by damage mechanism is provided in API 579-1/ASME FFS-1. A complete listing of the flaw and damage assessment procedures is shown in Table 2.

Table 2 – Parts and Damage Mechanisms in API 579-1/ASME FFS-1

| Part   | Overview  |
|--------|---|
| Part 1 | Introduction<br>Annex 1A – Glossary of Terms and Definitions                                      |
| Part 2 | Fitness-For-Service Engineering Assessment Procedure<br>Annex 2A – Technical Basis and Validation |

Table 2 – Parts and Damage Mechanisms in API 579-1/ASME FFS-1

| Part    | Overview  |
|---------|---|
|         | Annex 2B – Damage Mechanisms<br>Annex 2C – Thickness, MAWP and Stress Equations for a FFS Assessment<br>Annex 2D – Stress Analysis Overview for a FFS Assessment<br>Annex 2E – Material Properties for Stress Analysis<br>Annex 2F – Recommendations for Setting an Allowable RSF   |
| Part 3  | Brittle Fracture.<br>Annex 3A – Technical Basis and Validation: Assessment of Existing Equipment for Brittle Fracture   |
| Part 4  | General Metal Loss<br>Annex 4A – Technical Basis and Validation: Assessment of General Metal Loss   |
| Part 5  | Local Metal Loss<br>Annex 5A – Technical Basis and Validation: Assessment of Local Metal Loss   |
| Part 6  | Pitting Corrosion<br>Annex 6A – Technical Basis and Validation: Assessment of Pitting Corrosion   |
| Part 7  | Hydrogen Blisters, HIC and SOHIC Damage<br>Annex 7A – Technical Basis and Validation: Assessment of Hydrogen Blisters and Hydrogen Damage Associated with HIC and SOHIC   |
| Part 8  | Weld Misalignment and Shell Distortions<br>Annex 8A – Technical Basis and Validation: Assessment of Weld Misalignment and Shell Distortions   |
| Part 9  | Crack-Like Flaws<br>Annex 9A – Technical Basis and Validation: Assessment of Crack-Like Flaws<br>Annex 9B – Compendium of Stress Intensity Factor Solutions<br>Annex 9C – Compendium of Reference Stress Solutions<br>Annex 9D – Residual Stresses in a Fitness-For-Service Evaluation<br>Annex 9E – Crack Opening Areas<br>Annex 9F – Fracture Toughness<br>Annex 9G – Stress Analysis Overview for Crack-Like Flaws |
| Part 10 | High Temperature Operation and Creep<br>Annex 10A – Technical Basis and Validation: Assessment of Components Operating in the Creep Range<br>Annex 10B – Material Data for Creep Analysis   |
| Part 11 | Fire Damage<br>Annex 11A – Technical Basis and Validation: Assessment of Fire Damage<br>Annex 11B – Metallurgical Investigation and Evaluation of Mechanical Properties in Fire Damage Assessment   |
| Part 12 | Dent And Dent-Gouge Combinations<br>Annex 12A – Technical Basis and Validation: Assessment of Dents, Gouges, and Dent-Gouge Combinations  |
| Part 13 | Laminations<br>Annex 13A – Technical Basis and Validation: Assessment of Laminations  |
| Part 14 | Fatigue<br>Annex 14A – Technical Basis and Validation: Assessment of Fatigue Damage<br>Annex 14B – Material Data for Fatigue Analysis<br>Annex 14C – Plasticity Correction and Cycle Counting   |

## 2.2. FFS Eight-Step Assessment Procedure

The FFS Eight-Step Assessment Procedure used in API 579-1/ASME FFS-for all damage mechanisms is provided in Part 2 and is summarized in Table 3. Note that the first STEP in the assessment procedure is the identification of damage mechanisms; this will be discussed in paragraph 2.3.

Table 3 – Eight STEP Assessment Procedures in API 579-1/ASME FFS-1

| STEP | Description   |
|------|---|
| 1    | Flaw and Damage Mechanism Identification: The first STEP in a Fitness-For-Service assessment is to identify the flaw type and cause of damage. The original design and fabrication practices, the material of construction, and the service history and environmental conditions can be used to ascertain the likely cause of the damage. Once the flaw type and cause of damage are identified, the appropriate Part of this Standard can be selected for the assessment.  |
| 2    | Applicability and Limitations of the FFS Assessment Procedures: The applicability and limitations of the assessment procedure are described in each Part, and a decision on whether to proceed with an assessment can be made.  |
| 3    | Data Requirements: The data required for a FFS assessment depend on the flaw type or damage mechanism being evaluated. Data requirements may include; original equipment design data, information pertaining to maintenance and operational history, expected future service, and data specific to the FFS assessment such as flaw size, state of stress in the component at the location of the flaw, and material properties. Data requirements common to all FFS assessment procedures are covered in this Part. Data requirements specific to a damage mechanism or flaw type are covered in the Part containing the corresponding assessment procedures. |
| 4    | Assessment Techniques and Acceptance Criteria: Assessment techniques and acceptance criteria are provided in each Part. If multiple damage mechanisms are present, more than one Part may have to be used for the evaluation.   |
| 5    | Remaining Life Evaluation: An estimate of the remaining life should be made for establishing an inspection interval. The remaining life is established using the FFS assessment procedures with an estimate of future damage. The remaining life can be used in conjunction with an inspection code to establish an inspection interval.  |
| 6    | Remediation: Remediation methods are provided in each Part based on the damage mechanism or flaw type. In some cases, remediation techniques may be used to control future damage associated with flaw growth and/or material deterioration.  |
| 7    | In-Service Monitoring: Methods for in-service monitoring are provided in each Part based on the damage mechanism or flaw type. In-service monitoring may be used for those cases where a remaining life and inspection interval cannot adequately be established because of the complexities associated with the service environment. In-service monitoring may also be used along with a limiting flaw size to assure continued safe operation.  |
| 8    | Documentation: Documentation should include a record of all information and decisions made in each of the previous steps to qualify the component for continued operation. Documentation requirements common to all FFS assessment procedures are covered in Part 2. Documentation requirements specific to a damage mechanism or flaw are provided in subsequent Parts.  |

## 2.3. Identifying Damage Mechanisms

As identified in Table 3, the first STEP in a FFS assessment performed in accordance with API 579-1/ASME FFS-1 is to identify the flaw type and cause of damage. When conducting a FFS assessment it is important to determine the cause of the damage or deterioration observed and the likelihood and degree of further damage that might occur in the future. In order to assist the practitioner in identifying damage mechanisms, WRC Bulletins 488 [4], 489 [5], and 490 [6] have been published to cover damage mechanisms in the pulp and paper industry, the refining and petrochemical industry, and the fossil electric power industry, respectively. These WRC Bulletins provide guidance to the practitioner for the combined considerations of:

- Practical information on damage mechanisms that can affect process equipment,
- Assistance in determining the type, extent, and time-dependency of damage that can be expected, and
- How this knowledge can be applied to the selection of effective inspection methods to detect, size, and characterize the damage.

WRC Bulletin 489 has also been published as API 571 [7]. The contents of API 571 are currently being updated to provide guidelines for NDE, both detection and flaw sizing, for each damage mechanism. These guidelines are intended to supplement the NDE provisions in API 579-1/ASME FFS-1.

#### *2.4. Assessment Levels*

Three levels of assessment are provided in API 579-1/ASME FFS-1 for each flaw and damage type. In general, each assessment level provides a balance between conservatism, the amount of information required for the evaluation, the skill of the practitioner performing the assessment, and the complexity of analysis being performed. Level 1 is the most conservative and the easiest to use. Practitioners usually proceed sequentially from a Level 1 to a Level 3 assessment (unless otherwise directed by the assessment techniques), particularly if the current assessment level does not provide an acceptable result or a clear course of action cannot be determined.

It should be noted that the definitions of assessment levels in API 579-1/ASME FFS-1 are significantly different than those used in other standards. A general overview of each assessment level and its intended use is described below:

- Level 1 – The assessment procedures included in this level are intended to provide conservative screening criteria that can be utilized with a minimum amount of inspection or component information. The Level 1 assessment procedures may be used by either plant inspection or engineering personnel.
- Level 2 – The assessment procedures included in this level are intended to provide a more detailed evaluation that produces results that are less conservative than those from a Level 1 assessment. A Level 2 assessment requires inspection information similar to that needed for a Level 1 assessment; however, more detailed calculations are used in the evaluation. Level 2 assessments are typically conducted by plant engineers or engineering specialists' experienced and knowledgeable in performing FFS assessments.
- Level 3 – The assessment procedures included in this level are intended to provide the most detailed evaluation and produce results that are less conservative than those from a Level 2 assessment. In a Level 3 assessment, the most detailed inspection and component information is typically required. The recommended analysis is usually based on numerical techniques such as the finite element method. The Level 3 assessment procedures are primarily intended to be used by engineering specialists experienced and knowledgeable in performing FFS evaluations.

#### *2.5. Remaining Life and Rerating*

The FFS assessment procedures in API 579-1/ASME FFS-1 cover both the present integrity of the component given a current state of damage and the projected remaining life. If the results of a FFS assessment indicate that the equipment is suitable for the expected operating conditions, the equipment can continue to be operated at these conditions, as long as a suitable inspection program is established. If the results of the FFS assessment indicate that the equipment is not suitable for the expected operating conditions, calculation methods are provided in API 579-1/ASME FFS-1 to rerate the component. For pressurized components (e.g., pressure vessels and piping) these calculation methods can be used to find a reduced maximum allowable working pressure and/or coincident temperature. For tank components (i.e., shell courses) the calculation methods can be used to determine a reduced maximum fill height.

In API 579-1/ASME FFS-1, the remaining life calculation is used to establish an appropriate inspection interval in conjunction with the applicable in-service inspection code, provide information for an in-service monitoring plan, or to establish the need for remediation. API 579-1/ASME FFS-1 emphasizes the need for remediation where the remaining life cannot be established. Remediation can be in the form of altering the process stream, or isolating the process stream from the pressurized component by installation of a coating or lining, or the application of weld overlay. API 579-1/ASME FFS-1 also emphasizes the need for monitoring and inspection to validate the assumptions made about continuing damage.



## 2.6. Technical Basis

The technical basis and experimental validation of the FFS assessment procedures are summarized in Annex H of API 579-1/ASME FFS-1, and are published in a series of WRC Bulletins, see references [8, 19]. The API CRE FFS Committee is committed to publishing in the public domain the technical background to all FFS assessment procedures utilized in API 579-1/ASME FFS-1.

## 3. Part 9 – Crack-Like flaws

FFS assessment procedures for evaluating crack-like flaws in components are covered in API 579-1/ASME FFS-1, Part 9. Assessment procedures are provided to evaluate stationary cracks and subcritical crack-growth. There is special emphasis in the assessment procedures in this Part for evaluating subcritical crack-growth in pressure containing components. There are a wide variety of process environments and material degradation mechanisms that increase the occurrence of environmentally and service induced cracking, see API 571.

### 3.1. FAD Diagram

The Failure Assessment Diagram (FAD) is used for the evaluation of crack-like flaws in components. The FAD approach was adopted because it provides a convenient, technically based method to provide a measure for the acceptability of a component with a crack-like flaw when the failure mechanism is measured by two distinct criteria: unstable fracture and plastic collapse. Unstable fracture usually controls failure for flaws in components when the material of construction is in a brittle state, i.e. low toughness, and plastic collapse typically controls failure for large flaws if the material of construction is in a ductile state, i.e., high toughness. In a FFS analysis of crack-like flaws, the results from a stress analysis, stress intensity factor and reference stress solutions, the material strength, and fracture toughness are combined to calculate a toughness ratio,  $K_r$ , and load ratio,  $L_r$ . These two quantities represent the coordinates of a point that is plotted on a two-dimensional FAD to determine acceptability. If the assessment point is on or below the FAD curve, the component is suitable for continued operation. A schematic that illustrates the procedure for evaluating a crack-like flaw using the Failure Assessment Diagram is shown in Figure 1.

### 3.2. Subcritical Crack-Growth

In API 579-1/ASME FFS-1, in-service crack-growth may be categorized into five main types: crack-growth by fatigue, crack-growth by stress corrosion cracking, crack-growth by hydrogen assisted cracking, crack-growth by corrosion fatigue and combined cyclic and time dependent crack-growth, which are shown below:

$$\frac{da}{dN} = C \cdot \Delta K^n \quad (\text{Fatigue}) \quad (1)$$

$$\frac{da}{dt} = D \cdot K^m \quad (\text{Stress Corrosion, Corrosion Fatigue, Hydrogen Assisted}) \quad (2)$$

$$\frac{da}{dN} = \int \frac{da}{dt} + \frac{da}{dN} \quad (\text{Combined Cyclic \& Time-dependent}) \quad (3)$$

Other cyclic and time dependent subcritical growth equations such as Walker, Modified Forman, NASGRO, Colliopriest, ASME Section XI, and tri-linear equations may be used. An overview of these equations and applicable data is provided in API 579-1/ASME FFS-1, Annex 9F.

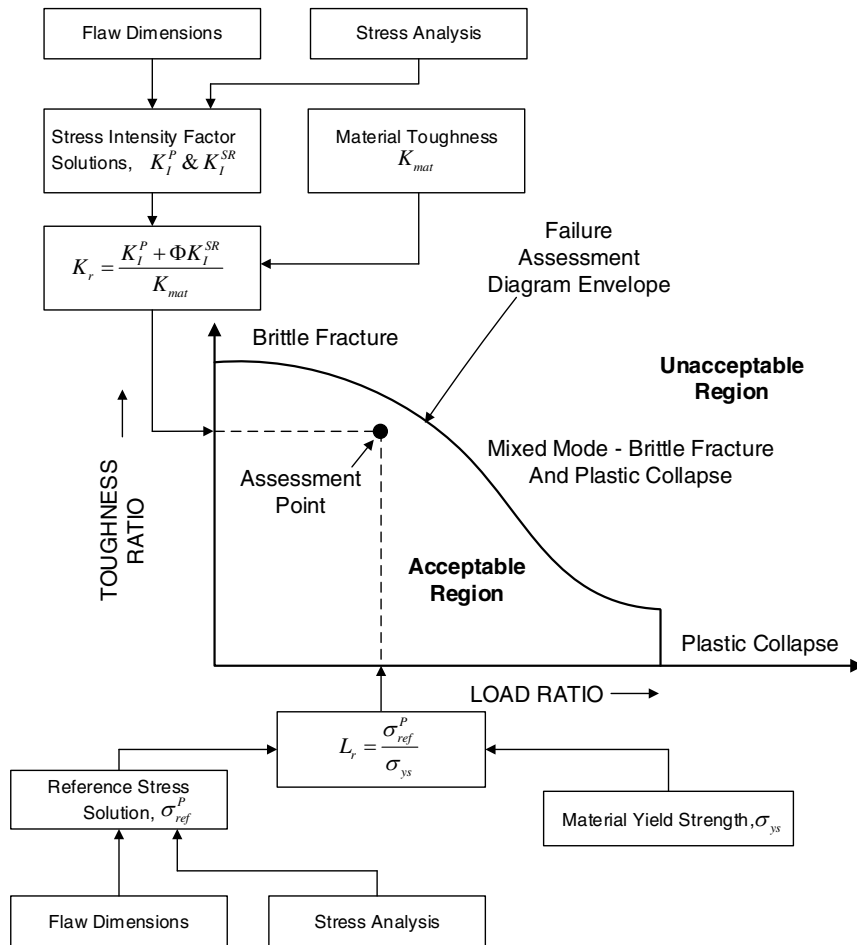


Fig. 1. – FAD Schematic

### 3.3. Subcritical Crack-Growth Procedure

Analysis of equipment containing growing cracks requires specialized skills, expertise, and experience because of the inherent uncertainties with the methodology. Therefore, in API 579-1/ASME FFS-1, an assessment of subcritical crack-growth requires a Level 3 Assessment. The Steps required in this type of analysis are summarized in Table 4.

Table 4 – Subcritical Crack-Growth procedure in API 579-1/ASME FFS-1, Part 9

| STEP | Description   |
|------|---|
| 1    | Perform a Level 3 Assessment, using Method A (FAD Assessment) for the initial crack size. If the component is demonstrated to be acceptable per a Level 3 Assessment, then attempt to apply remedial measures to prevent further crack-growth or proceed to STEP 2.   |
| 2    | If effective remedial measures are not possible and slow subcritical crack-growth is expected, then determine if a crack-growth model and associated data exist for the material and service environment. If a crack-growth model and data exist, then a crack-growth analysis can be performed. If crack-growth data does not exist, it may be determined in accordance with a recognized standard for crack-growth testing. |
| 3    | Compute the stress at the location of the flaw based on the future operating conditions. In these calculations, all relevant operating conditions including normal operation, start-up, upset, and shutdown should be considered.   |
| 4    | Determine an increment in crack-growth based on the previous flaw size, stress, estimated stress intensity, and the   |

Table 4 – Subcritical Crack-Growth procedure in API 579-1/ASME FFS-1, Part 9

| STEP | Description  |
|------|--|
|      | crack-growth model. To initialize the process, the previous flaw size is the initial flaw size determined in STEP 1. For surface and embedded flaws, the increment of crack-growth will have a component in the depth and length dimension. For embedded flaws, the increment of crack-growth may also include a component to model the flaw location in the wall thickness direction. The increment of crack-growth is established based on the applied stress intensity associated with the component containing the crack and the crack-growth equation. For example, if a surface flaw is being evaluated, the crack depth is incremented based on the stress intensity factor at the deepest portion of the crack and the length is incremented based on the stress intensity factor at the surface. The flaw size to be used in STEP 5 is the previous flaw size plus the increment of crack-growth.   |
| 5    | Perform a Level 3 Assessment for the current crack size. Demonstrate that for the current crack size, the point defined by the toughness ratio and load ratio is within the FAD. If the assessment point for the current flaw size is outside of the FAD or the crack is recategorized as a through-wall crack, then go to STEP 6; otherwise, go to STEP 4 and continue to grow the crack until the FAD is reached (see Figure 2).   |
| 6    | Determine the time or number of stress cycles for the current crack size, i.e., depth and length, to reach the limiting flaw size. The component is acceptable for continued operation provided: <ul style="list-style-type: none"> <li>• The time or number of cycles to reach the limiting flaw size, including an appropriate in-service margin, is more than that required for the operating period.</li> <li>• The crack-growth is monitored on-stream or during shutdowns, as applicable, by a validated technique.</li> <li>• The observed crack-growth rate is below the value used in the remaining life prediction as determined by an on-stream monitoring or inspections during shutdowns.</li> <li>• Upset conditions in loading or environmental severity are avoidable.</li> <li>• If the depth of the limiting flaw size is recategorized as a through-wall thickness crack, the conditions for an acceptable leak-before-break (LBB) criterion should be satisfied, see Part 9, paragraph 9.5.2.</li> </ul> |
| 7    | At the next inspection, establish the actual crack-growth rate, and re-evaluate the new flaw conditions per procedures of this Part. Alternatively, repair or replace the component or apply effective mitigation measures.  |

Note that in Step 5 the FAD assessment point for the current crack size is continuously plotted during subcritical crack-growth. These assessment points form a trajectory that ultimately intersects the FAD limiting envelope. The number of cycles and/or time for this to occur is defined as the remaining life (see Figure 2). The overall evaluation methodology for growing cracks is shown in Figure 3 and guidance for conducting a crack-growth analysis is shown in Figure 4.

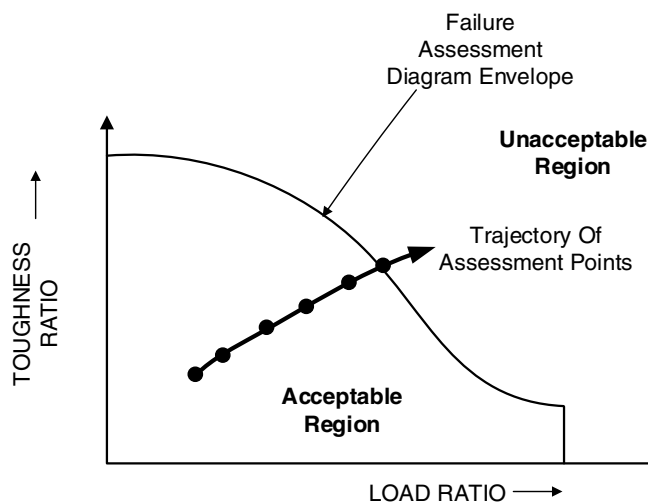


Fig. 2. – Trajectory of FAD Points During Subcritical Crack-Growth

#### 4. Part 14 – Fatigue

A new Part 14 pertaining to the assessment of fatigue damage from variable amplitude loading has been developed. The fatigue rules in ASME Section VIII, Division 2, Part 5 were used as a starting point to develop Part 14. In Section VIII, Division 2, the analysis methods for fatigue and the associated fatigue curves are presented in two forms: fatigue analysis method and curves that are based on smooth bar test specimens, and fatigue analysis method and curves that are based on test specimens that include weld details of the quality consistent with code construction. This same approach was followed for Part 14; therefore, the assessment procedures in Part 14 may be summarized as follows:

- Smooth bar fatigue assessment methods and curves may be used for components with or without welds. The welded joint fatigue assessment method and curves shall only be used for welded joints.
- The smooth bar fatigue assessment methods and curves are applicable up to the maximum number of cycles given on the curves. The welded joint fatigue assessment methods and curves do not exhibit an endurance limit and may be used for any number of cycles.
- If welded joint fatigue assessment methods and curves are used in the evaluation and thermal transients result in a through-thickness stress difference at any time that is greater than the steady state difference, then the number of design cycles shall be determined as the smaller of the number of cycles for the base metal established using smooth bar fatigue method, and the number of cycles for the weld established using the welded joint fatigue method.

In the creation of Part 14, major enhancements have been made including the addition of cycle counting procedures for all methods that can be used for proportional and non-proportional loading, recognition of the Uniform Material Law to generate fatigue-life curves and cyclic stress-strain curves, addition of a new fatigue method based on a critical plane approach, and an incremental Neuber plasticity correction that can be used for proportional and non-proportional loading.

##### *4.1. Level 1 Fatigue Assessment – Screening*

The Level 1 Assessment procedure is a fatigue screening criterion that is used to determine if a detailed fatigue assessment is required. If any one of the screening methods is satisfied, then a detailed fatigue analysis is not required as part of the FFS assessment.

- Method A – Experience with comparable equipment operating under similar conditions.
- Method B – Screening based on materials of construction (limited applicability), construction details, loading history, and smooth bar fatigue curve data.
- Method C – Screening based on the materials of construction (unlimited applicability), construction details, loading history, and smooth bar fatigue curve data.
- Method D – Screening based on the materials of construction (limited applicability), construction details, loading history, and welded joint fatigue curve data.

The fatigue exemption is performed on a component or part basis. One component (integral) may be exempt, while another component (non-integral) is not exempt. If any one component is not exempt, then a fatigue evaluation shall be performed for that component. If the specified number of cycles is greater than  $(10)^6$  cycles, then the screening criteria are not applicable and a fatigue analysis is required.

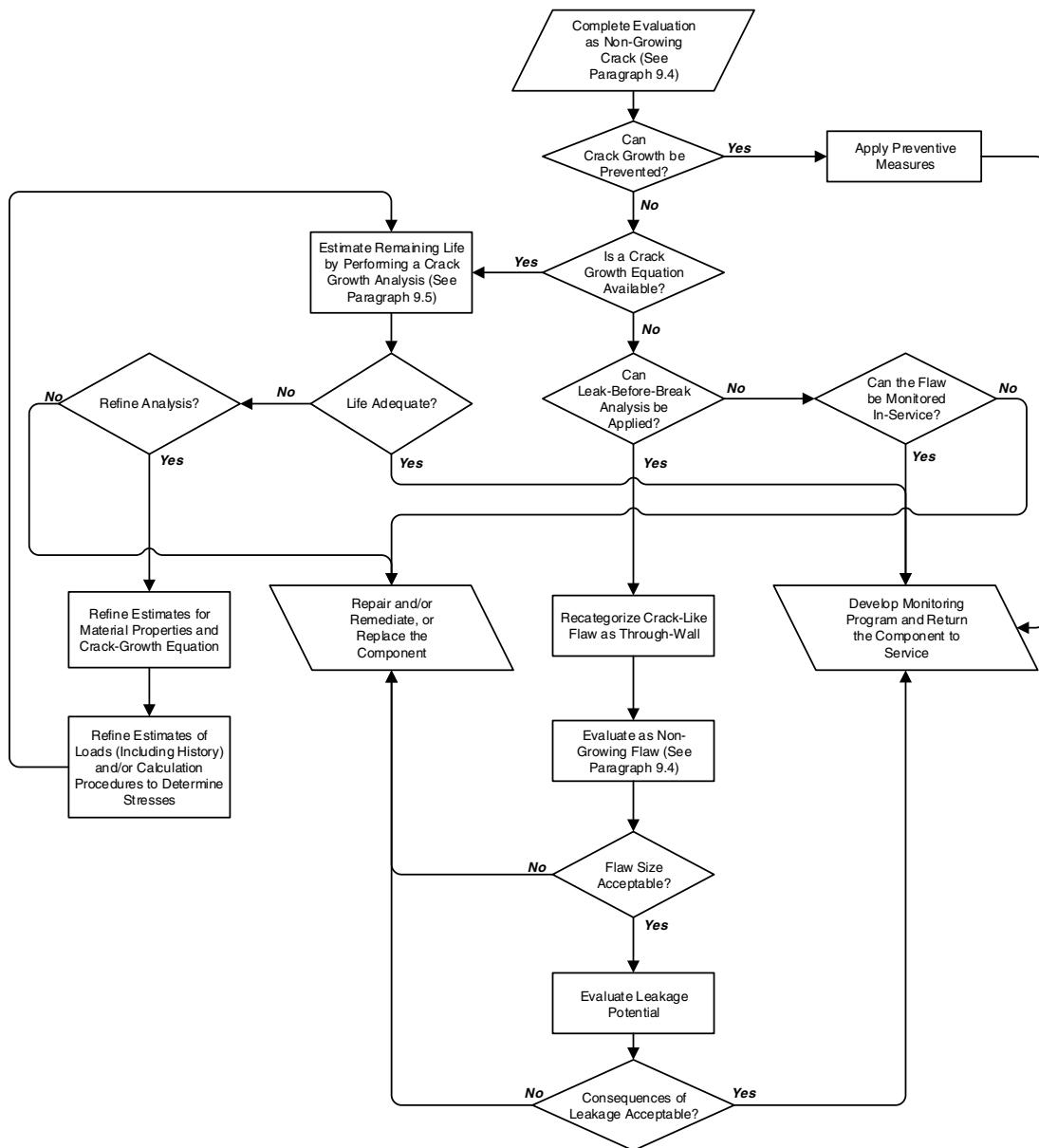


Fig. 3. – Overview of the Assessment Procedures to Evaluate Growing Crack-Like Flaws

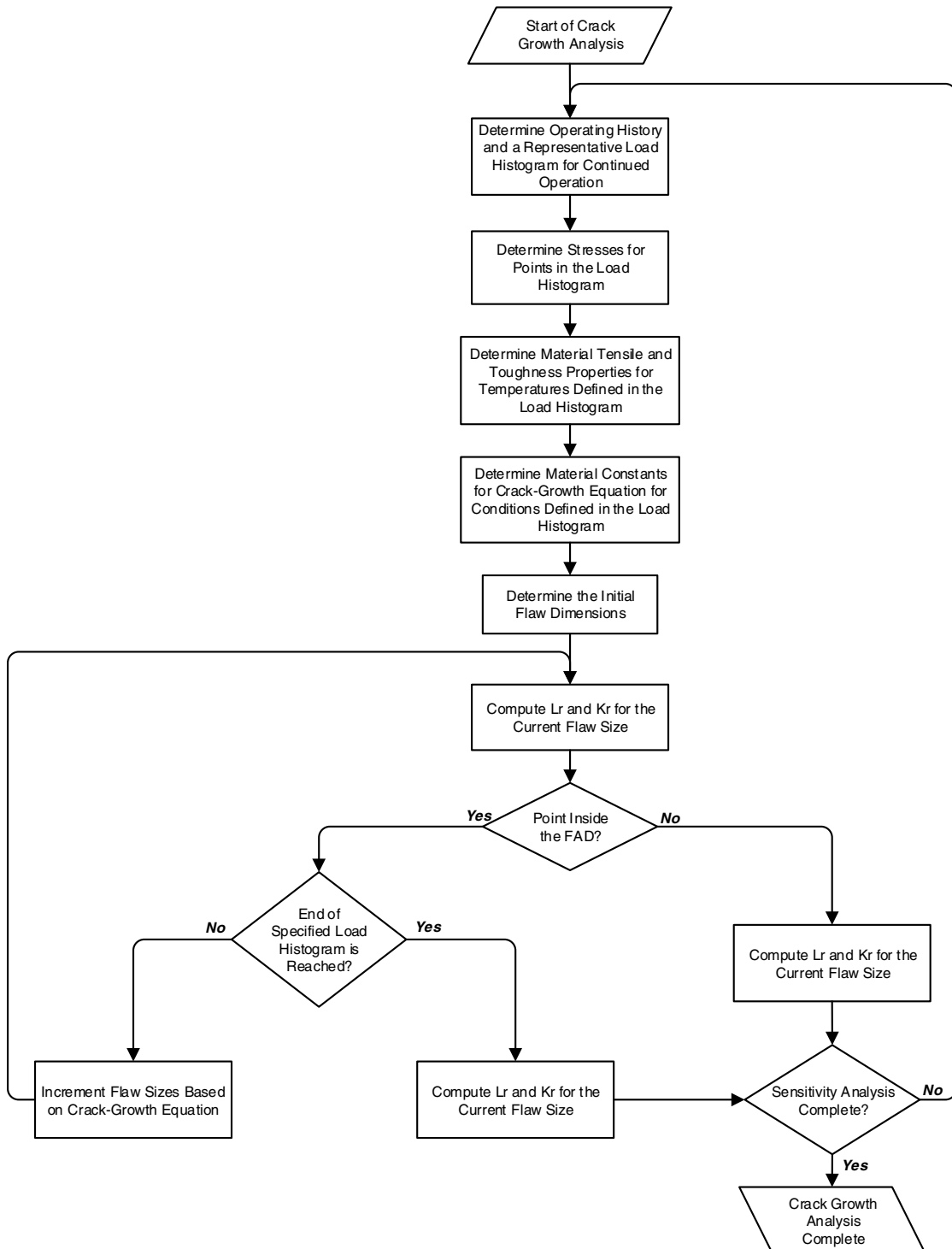


Fig. 4. – Methodology for Crack-growth Analysis

#### 4.2. Level 2 Fatigue Assessment – Overview

Three fatigue assessment methods are provided and are summarized below:

- Method A – Fatigue Assessment Using Elastic Stress Analysis and Equivalent Stresses. In this method, the fatigue damage and remaining life are computed based on effective total equivalent stress obtained from a linear elastic stress analysis, and a smooth bar fatigue curve.
- Method B – Fatigue Assessment Using Elastic-Plastic Stress Analysis and Equivalent Strain. In this method, the fatigue damage and remaining life are computed based on an effective strain range obtained from an elastic-plastic stress analysis, and a smooth bar fatigue curve.
- Method C – Fatigue Assessment of Welds Using the Equivalent Structural Stress. In this method, the fatigue damage and remaining life are computed based on an equivalent structural stress range parameter obtained from a linear elastic stress analysis, and a welded joint fatigue curve.

#### 4.3. Level 2 Fatigue Assessment – Method A

In Method A the effective total equivalent stress amplitude is used to evaluate the fatigue damage for results obtained from a linear elastic stress analysis. The controlling stress for the fatigue evaluation is the primary plus secondary plus peak equivalent stress amplitude that is defined as one-half of the primary plus secondary plus peak stress equivalent stress range,  $(P_L + P_b + Q + F)$ , calculated for each cycle in the loading history. Figure 5 taken from the ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, is a graphical representation of the stress calculations and classifications used with a linear elastic stress analysis. The primary plus secondary plus peak stress equivalent stress range is the equivalent stress, derived from the highest value across the thickness of a section, of the combination of all primary, secondary, and peak stresses produced by specified operating pressures and other mechanical loads and by general and local thermal effects and including the effects of gross and local structural discontinuities.

The Method A procedure represents the ASME fatigue design method developed in the 1960's that has survived basically unaltered. The procedure was updated in 2007 to calculate the alternating stress amplitude for the  $k^{th}$  cycle using component stress differences as shown below. The plasticity correction factor in this equation,  $K_{e,k}$ , is fully described in reference [20] and remains unchanged after 50 years.

$$S_{alt,k} = \frac{K_{e,k} \cdot \Delta S_{P,k}}{2} \quad (4)$$

$$\Delta S_{P,k} = \frac{1}{\sqrt{2}} \left[ \left( \Delta \sigma_{11,k} - \Delta \sigma_{22,k} \right)^2 + \left( \Delta \sigma_{11,k} - \Delta \sigma_{33,k} \right)^2 + \left( \Delta \sigma_{22,k} - \Delta \sigma_{33,k} \right)^2 + 6 \left( \Delta \sigma_{12,k}^2 + \Delta \sigma_{13,k}^2 + \Delta \sigma_{23,k}^2 \right) \right]^{0.5} \quad (5)$$

For implementation of this method into API 579-1/ASME FFS-1, it was decided not to alter the method for computing the alternating stress amplitude. However, a new multiaxial cycle counting routine has been added to identify the  $k^{th}$  cycles for variable amplitude loading [21].

The fatigue curve used to determine the permissible number of cycles is based on smooth bar test results and is shown in Figure 6. This fatigue curve is applicable to for carbon, low alloy, series 4xx, high alloy steels, and high tensile strength steels for temperatures not exceeding 371°C. The cusp in the curve at approximately 10,000 cycles is a result of the design margins included in the curve. The design margin for each point on the curve is set based on taking the minimum of the stress amplitude divided by two and the number of cycles divided by 20. The factor of 20 on cycles is the product of the following sub-factors [20].

- Scatter of data (minimum to mean) – 2.0
- Size effect – 2.5
- Surface finish, atmospheric, etc. – 4.0

| Stress Category                               | Primary  |   |  | Secondary Membrane plus Bending  | Peak   |
|---|--|---|--|--|--|
|   | General Membrane   | Local Membrane  | Bending  |  |  |
| Description (see Annex 2D and VIII-2, Part 5) | Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads. | Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads. | Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads. | Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations. | <ol style="list-style-type: none"> <li>1. Increment added to primary or secondary stress by a concentration (notch).</li> <li>2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.</li> </ol> |
| Symbol  | $P_m$  | $P_L$   | $P_b$  | $Q$  | $F$  |

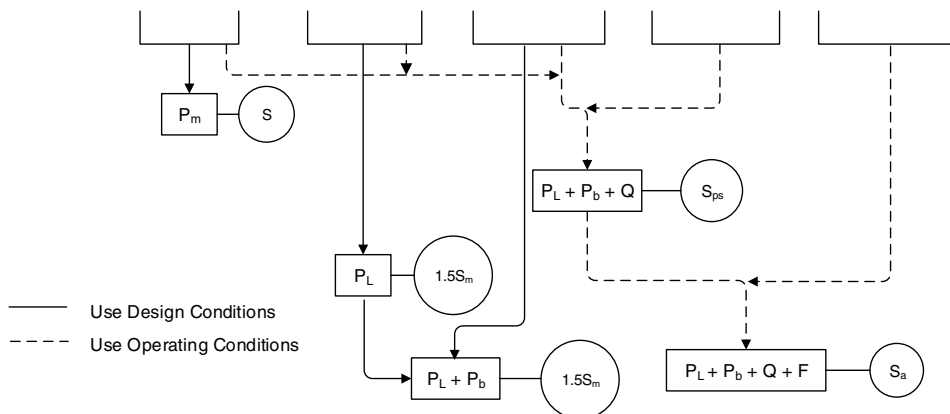


Fig. 5. – Level 2 Method A Fatigue Assessment Procedure



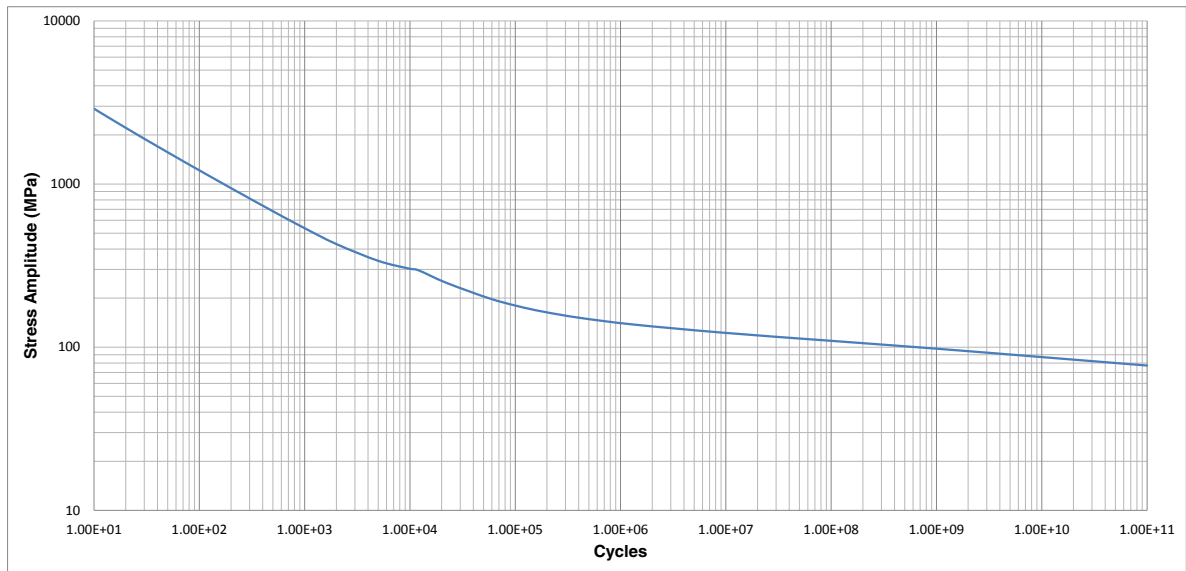


Fig. 6. – Method A and Method B Fatigue Curve Based on Smooth Bar Test Results

A flow diagram for the Method A procedure is shown in Figure 7.

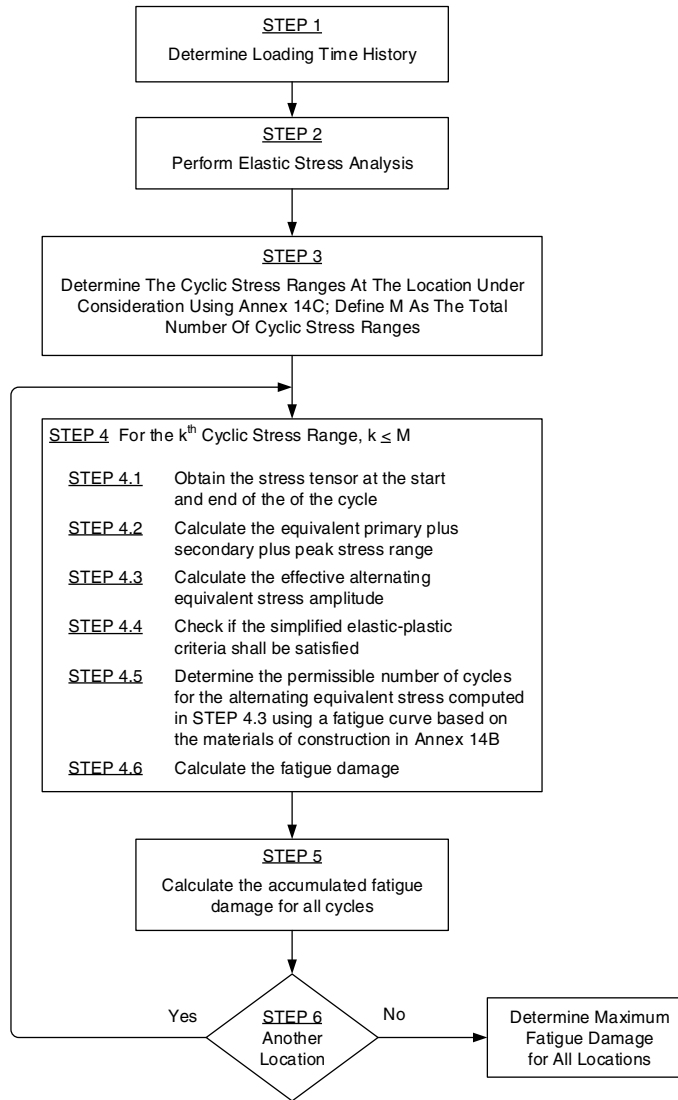


Fig. 7. – Method A Fatigue Assessment Procedure

#### 4.4. Level 2 Fatigue Assessment – Method B

In Method B, an effective strain range is used to evaluate the fatigue damage based on the results from an elastic-plastic stress analysis. This analysis is performed for the complete loading time history using a cyclic plasticity algorithm with kinematic hardening. The effective strain range is calculated using the equation shown below for the  $k^{th}$  cycle identified using a multiaxial cycle counting procedure as described in reference [20].

$$S_{alt,k} = \frac{E_{yf} \cdot \Delta \varepsilon_{eff,k}}{2} \quad (6)$$

$$\Delta \varepsilon_{eff,k} = \Delta \varepsilon_{e,k} + \Delta \varepsilon_{peq,k} \quad (7)$$

$$\Delta \varepsilon_{e,k} = \frac{1}{\sqrt{2}} \left[ \left( \Delta e_{11,k} - \Delta e_{22,k} \right)^2 + \left( \Delta e_{22,k} - \Delta e_{33,k} \right)^2 + \left( \Delta e_{33,k} - \Delta e_{11,k} \right)^2 + 6 \left( \Delta e_{12,k}^2 + \Delta e_{23,k}^2 + \Delta e_{31,k}^2 \right) \right]^{0.5} \quad (8)$$

$$\Delta \varepsilon_{peq,k} = \frac{\sqrt{2}}{3} \left[ \left( \Delta p_{11,k} - \Delta p_{22,k} \right)^2 + \left( \Delta p_{22,k} - \Delta p_{33,k} \right)^2 + \left( \Delta p_{33,k} - \Delta p_{11,k} \right)^2 + 1.5 \left( \Delta p_{12,k}^2 + \Delta p_{23,k}^2 + \Delta p_{31,k}^2 \right) \right]^{0.5} \quad (9)$$

Though computationally expensive, this method has the advantage of evaluating plastic strains accurately even with significant net-section plasticity and is effective for many low-cycle fatigue problems with simple load time histories. This method is currently attractive for evaluating low-cycle fatigue for loading time histories that do not have much variation. The attractiveness of Method B will gain popularity as computing capabilities, i.e., CPU and speed, evolve. For simple loading time histories the Twice Yield Method based on Massing's hypothesis may be used in lieu of a cycle-by-cycle analysis.

The fatigue curve used to determine the permissible number of cycles is the same as for Method A (see Figure 6). A flow diagram for the Method B procedure is shown in Figure 8.

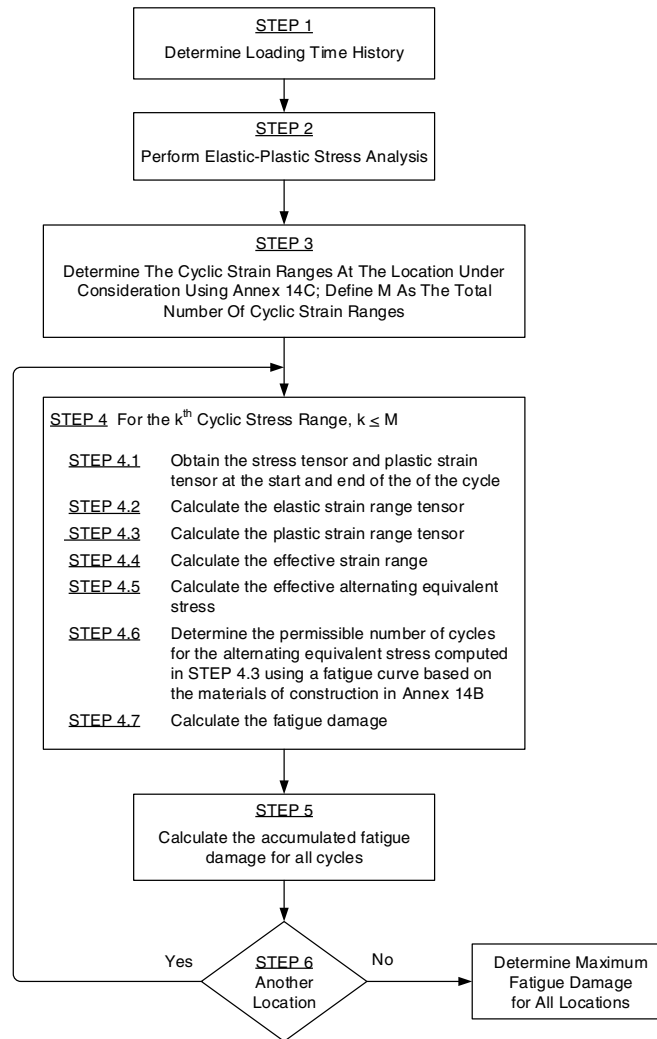


Fig. 8. – Method B Fatigue Assessment Procedure

#### 4.5. Level 2 Fatigue Assessment – Method C

Method C is intended for the evaluation of welded joints. In this method, the equivalent structural stress range parameter is used to evaluate the fatigue damage for results obtained from a linear elastic stress analysis. The controlling stress for the fatigue evaluation is the equivalent structural stress that is a function of the membrane and bending stresses normal to a hypothetical crack plane, the plane on which a fatigue crack would occur. The basic equations are shown below.

$$\Delta S_{ess,k} = \frac{\Delta \sigma_k}{t_{ess}^{\left(\frac{2-m_{ss}}{2m_{ss}}\right)} \cdot I^{m_{ss}} \cdot f_{M,k}} \quad (10)$$

$$\Delta \sigma_k^e = \Delta \sigma_{m,k}^e + \Delta \sigma_{b,k}^e \quad (11)$$

$$\Delta \varepsilon_k^e = \frac{\Delta \sigma_k^e}{E_{ya,k}} \quad (12)$$

$$\Delta \sigma_k \cdot \Delta \varepsilon_k = \Delta \sigma_k^e \cdot \Delta \varepsilon_k^e \quad (13)$$

$$\Delta \varepsilon_k = \frac{\Delta \sigma_k}{E_{ya,k}} + 2 \left( \frac{\Delta \sigma_k}{2K_{css}} \right)^{\frac{1}{n_{css}}} \quad (14)$$

$$m_{ss} = 3.6 \quad (15)$$

$$\begin{aligned} t_{ess} &= 16 \text{ mm} & \text{for } t \leq 16 \text{ mm} \\ t_{ess} &= t & \text{for } 16 \text{ mm} < t < 150 \text{ mm} \\ t_{ess} &= 150 \text{ mm} & \text{for } t \geq 150 \text{ mm} \end{aligned} \quad (16)$$

$$I_{m_{ss}}^{\frac{1}{m_{ss}}} = \frac{1.23 - 0.364R_{b,k} - 0.17R_{b,k}^2}{1.007 - 0.306R_{b,k} - 0.178R_{b,k}^2} \quad (17)$$

$$R_{b,k} = \frac{|\Delta \sigma_{b,k}^e|}{|\Delta \sigma_{m,k}^e| + |\Delta \sigma_{b,k}^e|} \quad (18)$$

$$f_{M,k} = (1 - R_k)^{\frac{1}{m_{ss}}} \quad \text{for } \sigma_{mean,k} \geq 0.5S_{y,k} \text{ and } R_k > 0 \text{ and } |\Delta \sigma_{m,k}^e + \Delta \sigma_{b,k}^e| \leq 2S_{y,k} \quad (19)$$

$$f_{M,k} = 1.0 \quad \text{for } \sigma_{mean,k} < 0.5S_{y,k} \text{ or } R_k \leq 0 \text{ or } |\Delta \sigma_{m,k}^e + \Delta \sigma_{b,k}^e| > 2S_{y,k} \quad (20)$$

$$R_k = \frac{\sigma_{min,k}}{\sigma_{max,k}} \quad (21)$$

Note that a Neuber correction is included in the analysis by solving Equations (13) and (14) for  $\Delta \sigma_k$  that is subsequently used in Equation (9) to compute the alternating stress range.

This method is recommended for evaluation of welded joints that have not been machined to a smooth profile. Welded joints with controlled smooth profiles may also be evaluated using Method A or Method B with a suitable fatigue strength reduction factor. If thermal transients result in a through-thickness stress difference at any time that is greater than the steady state difference, the number of design cycles shall be determined as the smaller of the number of cycles for the base metal established using Method A or Method B, and the number of cycles for the weld established using Method C

The fatigue curve used to determine the permissible number of cycles is based on welded joints and is shown in Figure 9. A flow diagram for the Method C procedure is shown in Figure 10.

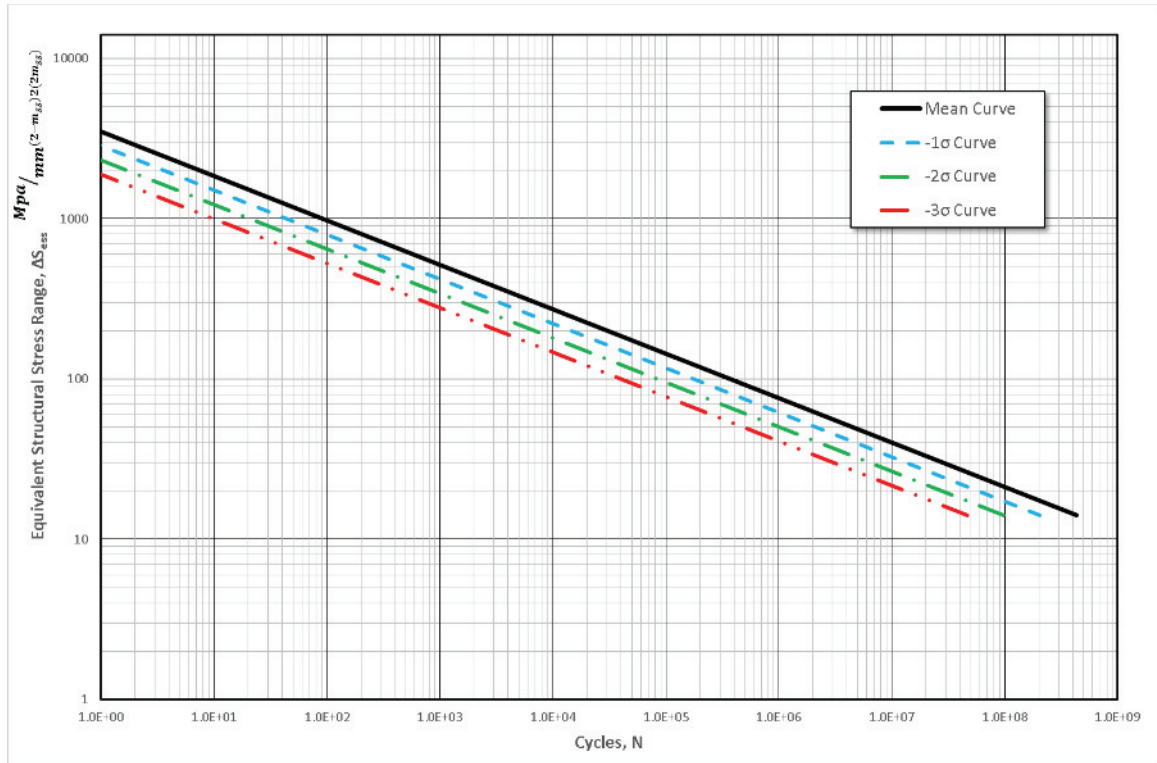


Fig. 9 – Method C Fatigue Curve Based on Welded Joints

The addition of welded joint fatigue technology to API 579-1/ASME FFS-1 and the ASME B&PV Code, Section VIII, Division 2 represented a significant departure from the legacy ASME Code methods; however, it also resulted in a significant upgrade to the evaluation methods for welded joints more in line with other international codes and standards. Plans to upgrade the welded joint method based on the Structural Strain approach, see reference [22], are currently in progress but will not be included in the 2015 Edition of API 579-1/ASME FFS-1. In the upgrade to these rules, a different approach is taken for plasticity correction and the hope is to develop more rational rules for ratcheting.

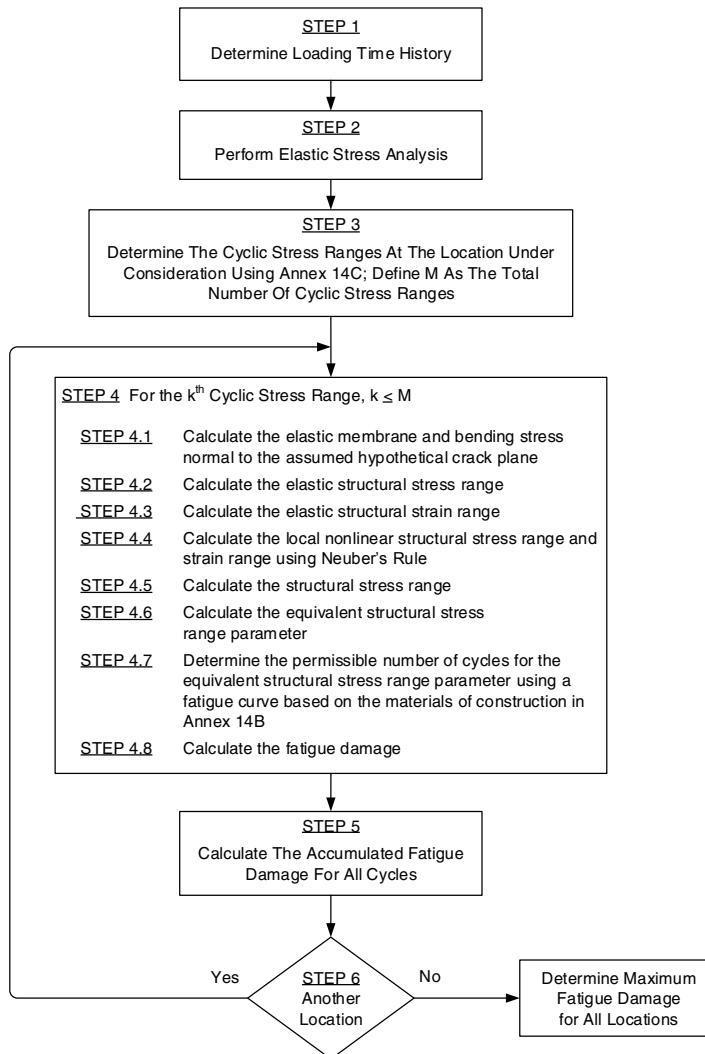


Fig. 10 – Method C Fatigue Assessment Procedure

#### 4.6. Level 2 Assessments Methods – Technical Background and Comparison

The technical background to the Level 2 Method A, Method B and Method C fatigue assessment procedures is provided in reference [20]. A comparison of the methods is shown in Table 5 in terms of the driving force for the fatigue damage, alternating stress range, and the resistance to fatigue damage, the fatigue curve.

Table 5 – Comparison of Fatigue Analysis Methods

| Methods A & B (Smooth Bar Fatigue Curves)   | Method C (Welded Joint Fatigue Curves)   |
|---|--|
| <b>Driving Force – Stress Measure:</b> <ul style="list-style-type: none"> <li>• Peak stress intensity from FEA continuum model</li> <li>• Method A: peak elastic stress directly from analysis or derived from linearized membrane and bending stress intensity against which a FSRF, <math>K_f</math>, is applied</li> <li>• Method B: equivalent elastic stress from total strains, i.e. elastic plus plastic strains</li> <li>• Stress linearization can be mesh sensitive, e.g., coarse mesh or 3D geometries</li> <li>• Fatigue penalty factor in terms of <math>K_e</math> for plasticity correction</li> <li>• Poisson's adjustment in terms of <math>K_v</math></li> <li>• Mean stress adjustment in fatigue curve</li> <li>• Multi-axial effects accounted for using stress intensity or equivalent stress</li> <li>• Fatigue improvement, must use <math>K_f</math></li> <li>• Weld toe defect correction, must use <math>K_f</math></li> </ul> | <b>Driving Force – Stress measure:</b> <ul style="list-style-type: none"> <li>• Membrane and bending stress normal to assumed defect orientation derived from nodal forces</li> <li>• Stress linearization to computed structural stress is mesh-insensitive and applicable for both 2D, 3D and shell/solid models</li> <li>• Neuber's method for plasticity correction</li> <li>• Poisson's adjustment for biaxial loading</li> <li>• Mean stress adjustment in term of R-ratio</li> <li>• Multi-axial effects considered</li> <li>• Fatigue improvement factor explicitly included</li> <li>• Weld toe defect correction available</li> </ul>  |
| <b>Resistance – Design Fatigue Curve:</b> <ul style="list-style-type: none"> <li>• Mean stress adjustment included in the fatigue curve</li> <li>• Implicit margins applied to smooth bar mean curve (2 on stress and 20 on cycles) to cover: <ul style="list-style-type: none"> <li>○ Scatter</li> <li>○ Size effects</li> <li>○ Surface condition &amp; Environment</li> </ul> </li> </ul>  | <b>Resistance – Design fatigue curve:</b> <ul style="list-style-type: none"> <li>• Mean stress adjustment: included in structural stress driving force formulation</li> <li>• Explicit margins provided to welded joint fatigue curves <ul style="list-style-type: none"> <li>○ Scatter: characterized by statistical measure of a large amount of actual weld S-N air data</li> <li>○ Size effects: included in structural stress driving force formulation</li> <li>○ Environment (<math>f_E</math>): not included in fatigue data scatter, explicit factor (e.g., 4) is applied</li> <li>○ Fatigue Improvement (<math>f_i</math>)</li> </ul> </li> <li>• Implicit margins, contained in fatigue scatter band <ul style="list-style-type: none"> <li>○ Surface condition including local notch effects</li> <li>○ Welding effects</li> </ul> </li> </ul> |

#### 4.7. Level 2 Ratcheting Assessment

In addition to the fatigue damage and remaining life methods, two methods are provided to evaluate the propensity for ratcheting. In the first method, the protection against ratcheting is evaluated using an elastic analysis with conservative assumptions to approximate the effects of steady-state and cyclic loading conditions. The Bree diagram is the basis for the elastic ratcheting rules, see reference [20]. In the second method, the protection against ratcheting is evaluated using an elastic-plastic analysis by directly calculating the plastic strain accumulation from steady-state and cyclic loading conditions in a numerical analysis.



#### 4.8. Level 3 Fatigue Assessment

The Level 3 assessment determines allowable fatigue cycles for a component and loading history using a multiaxial strain-life equation with a mean stress correction in combination with a critical plane approach. The critical plane approach resolves the stress-strain state at a given point on a number of candidate planes. Fatigue damage is calculated on each candidate plane using the strain-life equation, and the plane with the maximum damage identifies the critical plane and the overall fatigue damage for the given point. If an elastic-plastic analysis is performed using Level 2 Method B, strain results are post-processed directly. However, implementation of strain-life methods that utilize an elastic analysis are corrected for cyclic plasticity using a multiaxial Neuber correction based on a cyclic stress strain curve.

The Brown-Miller strain-life equation, adjusted for mean stress effects, shown below is used in the assessment [23].

$$\frac{\Delta\gamma_k}{2} + \frac{\Delta\epsilon_{N,k}}{2} = 1.65 \frac{\sigma'_{f,k} - \sigma_{N-mean,k}}{E_{ya,k}} (2N_{f,k})^{b_k} + 1.5 \epsilon'_{f,k} (2N_{f,k})^{c_k} \quad (22)$$

The cyclic stress-strain curve and associated fatigue curve are derived from the Uniform material Law [24]. Plasticity correction is accounted for using an incremental Neuber procedure suitable for non-proportional loading [23, 25]. The plasticity model incorporated is the multiple backstress, nonlinear kinematic-hardening model of Chaboche [26, 27]. A multi-channel rainflow procedure has also been developed to identify cycles on the critical planes, see reference [21]. A flow diagram for the Level 3 procedure is shown in Figure 11.

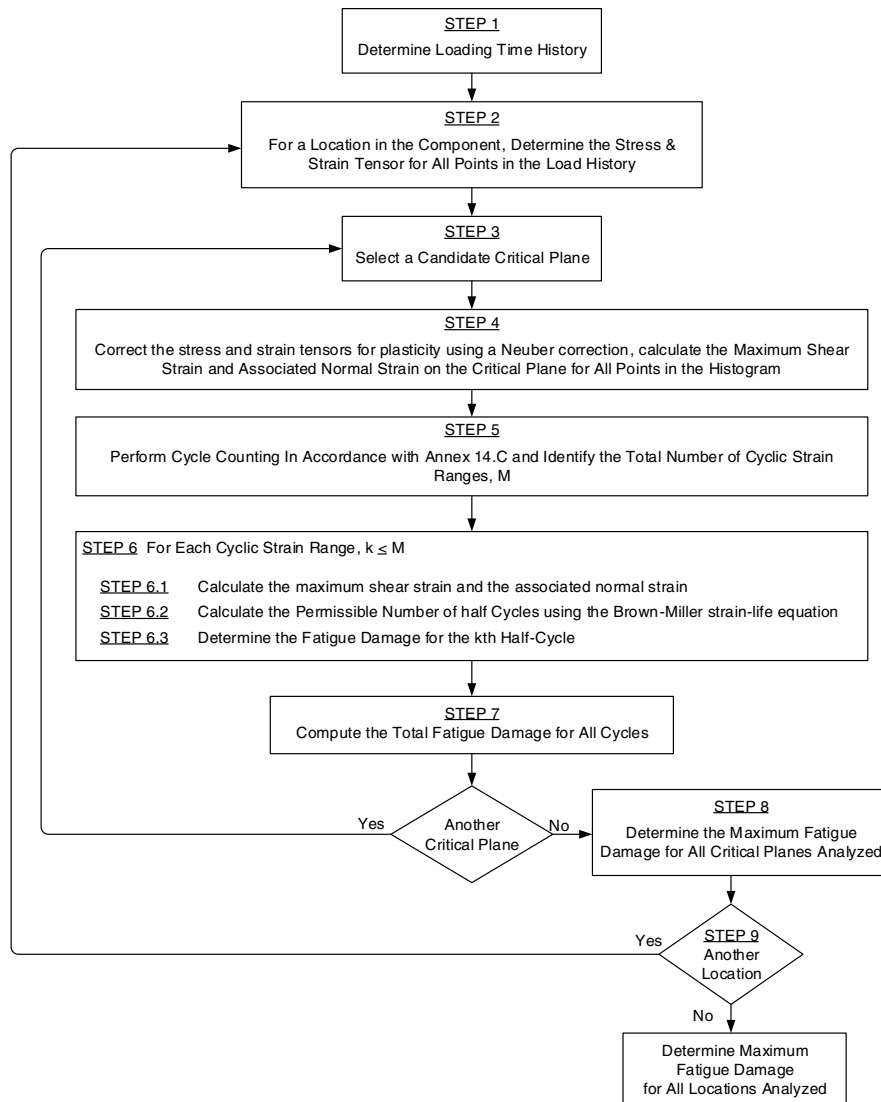


Fig. 11 – Level 3 Fatigue Assessment Procedure

#### 4.9. Standardization of Fatigue Methods for Use in API 579-1/ASME FFS-1 – Technical Background

A review of the literature indicates that excellent work has gone into developing robust methods for assessing fatigue damage. However, the great variety of methods, which are often slightly modified versions of one another, has made the choice of the most appropriate fatigue model unclear. In addition, the use of finite element analysis (FEA) methods in recent years necessitates a more systematic and precise algorithmic description of the various methods. Moreover, the fatigue methods in the ASME B&PV Code, Section VIII, Division 2 are dated; therefore, an added challenge is to introduce new fatigue methods to a community not familiar with more modern day fatigue analysis methods.

To provide a more consistent framework upon which to incorporate modern fatigue methods into API 579-1/ASME FFS-1, especially when using FEA codes to generate stress or strain loading data, a thorough review of existing methods has been conducted and documented in WRC Bulletin 549 [21]. A set of standardized methods for

performing fatigue analysis and the cycle counting required for variable amplitude, non-proportional loading is selected and presented in WRC Bulletin 549 in enough detail for a precise implementation in modern computer software. Example problems are also provided. A condensed version of WRC Bulletin 549 will be published as Annex 14C in the third edition of API 579-1/ASME FFS-1.

Three main algorithms for cycle counting are presented for variable amplitude conditions, and detailed step-by-step descriptions are given for each. The first is a uniaxial Rainflow method that is appropriate for a loading history that is represented by a single parameter. The second is the multiaxial Wang and Brown method that is appropriate for a general multiaxial loading history (stress or strain) with proportional or non-proportional loading. Finally, a modified rainflow method with multiple channels will be used in conjunction with the classical critical plane method, proposed as an alternative, multiaxial method for cases with non-proportional loading. For each method, the limitations and literature comparisons are discussed, and the results of fatigue damage assessments are compared.

In addition to cycle counting, a detailed algorithm for the Neuber plasticity correction is also provided. This is important for modern FEA fatigue analysis, where it is more efficient, especially for cases of high-cycle fatigue, to obtain elastic FEA results first and then post-process them to account for the leading-order plasticity effects. In many cases, this is shown to be an acceptable approximation to solving the full plasticity model, which is a much more time consuming endeavor. An incremental multiaxial Neuber plasticity correction using the nonlinear kinematic-hardening model of Chaboche is fully described in addition to alternative methods.

## 5. Summary

The API 579-1/ASME FFS-1 Standard was developed to provide guidance for conducting FFS assessments of flaws commonly encountered in the refining and petrochemical industry, that occur in pressure vessels, piping, and tankage. In the third edition of API 579-1/ASME FFS-1, two forms of fatigue will be addressed, crack initiation using a strain-life equation and subcritical crack-growth based on fracture mechanics.

The fracture mechanics methods used for subcritical crack-growth described herein are based on the FAD. The FAD provides a way to use the results from an elastic stress analysis with elastic fracture mechanics concepts to approximate elastic-plastic fracture and plastic collapse.

Part 14 covering the strain-life approach to fatigue is a new part in the third edition of API 579-1/ASME FFS-1. The four methods described that utilize strain-life techniques based on smooth bar and welded joint fatigue curves will be included in Part 14. These methods include the legacy ASME techniques that have been updated to include more modern cycle counting methods and a new critical plane approach based on the Brown-Miller strain-life equation, a rainflow cycle counting method with multiple channels, and an incremental multiaxial Neuber plasticity correction using the nonlinear kinematic-hardening model of Chaboche. The fatigue methods for welded joints, Level 2 Method C, will also be provided based on the implementation in the second edition of API 579-1/ASME FFS-1. However, an update to this method is already being evaluated for a future release.

The key aspect of the new fatigue rules in Part 14 involve incorporation of cycle counting procedures to be used with each method. In addition, the incremental Neuber plasticity correction used in the Level 3 Assessment represents a significant upgrade to the plasticity correction currently used in Level 2, Method A, i.e., the  $K_e$  factor. A WRC Bulletin is being prepared to ensure that these aspects are correctly implemented in a standard correctly and technically documented. This WRC Bulletin will be the basis for Annex 14C that will be included in API 579-1/ASME FFS-1.

## Acknowledgements

I would like to acknowledge the work of David Thornton, Phillip Prueter and David Dewees in helping to prepare the new Part 14 for API 579-1/ASME FFS-1. In addition, the work of Dr. Charles Panzarella, Dr. Edrissa Gassama, Dr. Aaron Stenta and Jeffery Cochran in developing WRC Bulletin 549 and Annex 14C of API 579-1/ASME FFS-1 is dully noted. Finally, I would like to acknowledge the help of Tiffany C. Shaughnessy for help in preparing this manuscript.

## References

- [1] Anderson, T.L., *Fracture Mechanics – Fundamentals and Applications*, 3rd Edition, CRC Press, Boca Raton, Florida, 2005.
- [2] API, API 579 Recommended Practice for Fitness-For-Service, American Petroleum Institute, Washington, D.C., 2000.
- [3] API, API 579-1/ASME FFS-1 2007 Fitness-For-Service, American Petroleum Institute, Washington, D.C., 2007.
- [4] Dobis, J.D. and Prager, M., Damage Mechanisms Affecting Fixed Equipment in the Pulp and Paper Industry, WRC Bulletin 488, Welding Research Council, 2004.
- [5] Dobis, J.D. and Prager, M., Damage Mechanisms Affecting Fixed Equipment in the Refining Industry, WRC Bulletin 489, Welding Research Council, 2004.
- [6] Dobis, J.D. and Prager, M., Damage Mechanisms Affecting Fixed Equipment in the Fossil Electric Power Industry, WRC Bulletin 490, Welding Research Council, 2004.
- [7] Scott, P.M., Anderson, T.L., Osage, D.A., and Wilkowski, G.M., Review of Existing Fitness-For-Service Criteria for Crack-Like Flaws, WRC Bulletin 430, The Welding Research Council, New York, N.Y., 1998.
- [8] API, API 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry, American Petroleum Institute, Washington, D.C.
- [9] Osage, D.A., Krishnaswamy, P., Stephens, D.R., Scott, P., Janelle, J., Mohran, R., and Wilkowski, G.M., Technologies For The Evaluation Of Non-Crack-like Flaws in Pressurized Components – Erosion/Corrosion, Pitting, Blisters, Shell Out-Of-Roundness, Weld Misalignment, Bulges, And Dents, WRC Bulletin 465, The Welding Research Council, New York, N.Y., April, 1998.
- [10] Anderson, T.L., Thorwald, G., Revelle, D.J., Osage, D.A., Janelle, J.L., and Fuhry, M.E., Development Of Stress Intensity Factor Solutions For Surface And Embedded Cracks In API 579, WRC Bulletin 471, The Welding Research Council, New York, N.Y., May 2002.
- [11] Anderson, T.L., Stress Intensity and Crack Growth Opening Area Solutions For Through-wall Cracks In Cylinders And Spheres, WRC Bulletin 478, Welding Research Council, January, 2003.
- [12] Dong, P., Cao, Z., Hong, J.K., Zhang, J., Brust, F., Bell, W., and McDonald, E.J., Recent Progress In Analysis of Welding Residual Stresses, WRC Bulletin 455, Welding Research Council, September, 2000.
- [13] Dong, P., and Hong, J.K., Recommendations for Determining Residual Stresses in Fitness-For-Service Assessments, WRC Bulletin 476, Welding Research Council, November, 2002.
- [14] Dong, P., Hong, J.K., Osage, D.A., and Prager, M., Master S-N Curve Method for Fatigue Evaluation of Welded Components, WRC Bulletin 474, Welding Research Council, August, 2002.
- [15] Janelle, J.A. and Osage, D.A., An Overview and Validation of the Fitness-For-Service Assessment Procedures for Local Thin Areas in API 579, WRC Bulletin 505, Welding Research Council, New York, N.Y., 2006.
- [16] Dong, P., Hong, J.K., Osage, D.A., Dewees, D. and Prager, M., The Master S-N Curve Method an Implementation for Fatigue Evaluation of Welded Components in the ASME B&PV Code, Section VIII, Division 2 and API 579-1/ASME FFS-1, WRC Bulletin 523, Welding Research Council, New York, N.Y.
- [17] Prager, M., Osage, D.A., Staats, J. and Macejko, B., Development Of Material Fracture Toughness Rules For ASME B&PV Code Section VIII Division 2, WRC Bulletin 528, Welding Research Council, New York, N.Y.
- [18] Staats, J.C., Buchheim, G.M., and Osage, D.A., Development of Fitness-for-Service Rules for the Assessment of Hydrogen Blisters, HIC and SOHIC, WRC Bulletin 531, Welding Research Council, New York, N.Y.
- [19] Dewees, D.J., Prueter, P.E., Kummari, S.R., Brown, R.G., Thome, T.L., Smith, K.J., Bifano, M.F.P., Panzarella, C.H., Osage, D.A., Development of Revised Weld Residual Stress Guidance for fitness-For-Service Assessments in API 579-1/ASME FFS-1, , Welding Research Council, New York, N.Y.
- [20] Osage, D.A. and Sowinski, J.S., ASME Section VIII – Division 2 Criteria and Commentary, ASME PTB-1, ASME, New York, N.Y., 2013.
- [21] Panzarella, C.H., Gassama, E. and Stenta, A., Cochran, J.D., Standardization of Fatigue Methods for Use in API 579-1/ASME FFS-1, WRC Bulletin 550, Welding Research Council, New York, N.Y., 2015.
- [22] Dong, P., Pei, X., Xing, S., and Kim, M.H., “A Structural Strain Method for Low-Cycle Fatigue Evaluation of Welded Components,” *International Journal of Pressure Vessels and Piping*, 119 (2014) 39-51.
- [23] Draper, J., *Modern Metal Fatigue Analysis*, EMAS Publishing, Warrington, UK, 2008.
- [24] Baumeister A. Jr and Seeger, T., *Materials Data for Cyclic Loading – Supplement 1*, Elsevier Science Publishing BV, 1987.
- [25] Lee, Y., Barkey, M.E., and Kang, H., *Metal Fatigue Analysis Handbook, Practical Problem-Solving Techniques For Computer Aided Engineering*, Elsevier, Inc., 2012.
- [26] Chaboche, J.L., “Time-Independent Constitutive Theories For Cyclic Plasticity,” *International Journal of Plasticity*, 2(2), 1986, pp. 149-188.
- [27] Dewees, D. J., “Application of Elastic-Plastic Design Data in the New ASME B&PV Code Section VIII Division 2,” PVP2010-25641, pp. 99-109, ASME 2010 Pressure Vessels and Piping Conference, ASME, 2010, New York.